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8th CIRP Conference on High Performance Cutting (HPC 2018)

Edge trimming of carbon fibre reinforced plastic

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Abstract

In recent years the use of Carbon Fibre Reinforced Plastic (CFRP) has transitioned towards mass manufacture applications, heightening the requirement to improve both the processing capability and production cost. Machining is a key process which CFRP components often undergo, in order to achieve final assembly requirements, however, it can introduce delamination, poor surface roughness and even result in component scrap. Furthermore, the rate of tool wear and subsequently cost of tooling can be high. This paper investigates the effect of cryogenic CNC machining using liquid nitrogen on tool wear and machined surface quality for edge trimming of CFRP using different cutting tool geometries. The results show that the cutting environment has a significant effect on CFRP surface roughness and delamination for both cutting tools beyond a short period of accelerated tool wear. The cryogenic environment improved the average surface roughness of samples by 28.1% independent of cutting tool geometry compared to dry machining. Improvement to delamination was only found in samples machined with the up-down compression cutting tool, which resulted in 49.9% reduction in delamination. The lack of improvement to delamination found with the multi-tooth cutting tool is likely due to increased prevalence of the chipping mode of tool wear in cryogenic cutting environment. In contrast, the abrasive wear zone of the up-down compression cutting tool exhibited higher sharpness than in dry machining and the geometry appears to be well suited for achieving improvements in surface quality and tool wear under cryogenic machining. This research indicated the high interaction between cutting tool geometry and machining environment.

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Keywords: Machining; CFRP; Carbon Fibre

1. Introduction

Carbon fibre reinforced plastics (CFRP) are an important class of composite material in the aerospace industry due to superior properties, such as high strength and stiffness, long fatigue life, low density, and high corrosion and wear resistances. With demand for high fuel efficiency and emission concerns driven by government policies also in the automotive industry to remain competitive, it is expected that use of CFRP will continue to grow and escalate to series production levels.

Although composite components are often made to a near-net shape, post-machining operations are often unavoidable as excess material is often added to ensure material conformity to complex mould shapes and for locating and work holding

purposes. Additionally, holes may be needed for joining purposes. The conventional methods most frequently used are edge trimming, milling, drilling, countersinking, turning, sawing, and grinding [1]. Carbon fibre composites require high-levels care and a high safety factor as the anisotropic and inhomogeneous nature of the fibre means the component can behave unexpectedly in the presence of a defect [2]. Post machining techniques in particular often do not meet the stringent quality requirements, due occurrence of damage modes including: fibre pull out, inter-ply delamination, matrix cracking, matrix burning, un-cut fibres and fibre-matrix debonding.

The machining of CFRP was shown by Koplev et al. [3] to be characterised by uncontrolled intermittent fracture and

elevated levels of abrasive tool wear. These two characterisations are distinctively different from typical metal machining, which is initiated by shearing and plastic deformation of the material by the cutting tool. The cutting speed in machining CFRP must be controlled such that the heat generated in the matrix does not exceed the glass transition temperature leading to irreversible damage and surface burning [4]. The matrix is less effective at constraining the reinforcement in this condition, encouraging fibre pull out, preventing a clean shear cut [5] and thus making CFRP a challenging material to machine.

For this reason, the cooling method and cutting tool design has been investigated to improve the quality of CFRP machining operations. Sheikh-Ahmad et al. [6] and Haddad et al. [7] found that using a multi-tooth tool appeared to minimise defects compared to conventional helical cutting tools in the dry condition. Karpát et al. [8] generated a force model for UD cutting tool, however literature showing the practical effects of the use of this cutting tool geometry is limited. Chen et al. [9] compare the performance of the up-down and multi-tooth chemical vapour deposition (CVD) coated cutting tools for CFRP. However, this was for drilling in a dry machining environment only.

Conventional oil based lubricants can be used to chill the cutting zone, however, are generally avoided due to absorption of the oil into porous machined surface. An alternative is presented with the use of cryogenic fluid. Improvements to the machinability of hard-to-machine exotic metals with cryogenic fluids has been demonstrated in great detail over 60 years, with targeted application to the cutting tool shown to give improvements in tool wear and surface finish [10]. However, there has been far less investigation into the use of cryogenic fluids for machining of composites. Bhattacharya et al. [11] showed the tool flank wear, cutting forces and surface roughness (R_a) displayed considerable improvement with continual flooding of LN_2 when drilling Kevlar Fibre Reinforced Polymer. Wang et al. [4] showed there is a critical increase the critical cutting speed at which matrix decomposition occurs could be increased in milling of the same material. This effect is beneficial as higher cutting speeds were linked to improved surface quality. Kim & Ramulu [12] showed cryogenically treated drill bits reduced thrust force and improvement surface roughness, fibre protrusion and delamination length in drilling CFRP although this was accompanied by higher tool wear. Chilled air has also been shown to reduce defects and increase tool life [13].

This research investigates the effect of cryogenic CNC machining on the edge trimming performance of CFRP for the multi-tooth and UD cutting tool. The surface roughness and delamination of samples in the cryogenic fluid and dry machining environment are established. The machined surfaces of the coupons and cutting tool wear are observed by scanning electron microscope (SEM) and optical microscopy to clarify the surface defect mechanism.

2. Methodology

CFRP coupons were supplied by National Composites Centre, Bristol UK. The composite consisted of Non Crimp

Fabric (NCF) comprised of 4 layers of $\pm 45^\circ$ carbon fibre stitched together with the pillar/chain pattern to form samples of 2.7mm constant thickness. NCF's lend themselves well to automation and large production quantities as the integrated layers. As there is no impregnation of resin also, draping qualities are improved [14]. The cutting tools investigated were multi-tooth and up-down (UD) in design as shown in Fig. 1 and both were sourced in uncoated carbide form from CERATIZIT WNT Ltd.

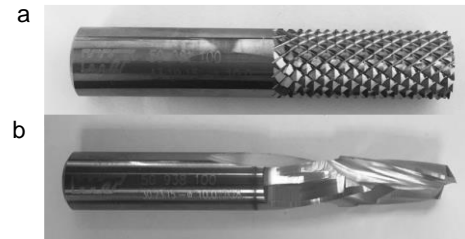


Figure 1. (a) Multi-tooth cutting tool; (b) up-down cutting tool

Experiments were conducted on a Bridgeport VMC 610XP² using the processing parameters displayed in table 1. Edge trimming was conducted with radial depths of cut of 1mm made centrally across the cutting tool length. The effect of using liquid nitrogen (LN_2) as cryogenic fluid during machining was compared to the dry machining condition using the cryogenic machining facility at the University of Bath [15]. This applies the cryogenic fluid through specialised nozzles which surround the rotating cutting tool and cools tool and workpiece simultaneously. This approach was found by Bhattacharya [11] to be the best cryogenic cooling approach, compared to pre-emersion of the cutting tool or workpiece.

Table 1. Processing parameters employed in the investigation

| Cutting Tool Design | Cutting tool material | Cutting Tool Diameter | Cutting speed | Cutting feed |
|---------------------|-----------------------|-----------------------|---------------|--------------|
| Multi-tooth UD | Uncoated Carbide | 10mm | 200m/min | 350mm/min |

A full factorial experimental design was developed as shown in table 2 and resulted in 16 experimental runs. Each cutting tool was used to machine four CFRP coupons in intervals to investigate the effect of tool wear. A preliminary tool wear check was performed at a machined length of 4.2m in preliminary testing to ensure machined lengths were adequate to initiate tool wear. Tool wear and delamination length of the top and underside of the samples was measured using a Leica DFC 425 optical microscope. The extent of delamination of the top surface was investigated with Flash thermography. The surface roughness of samples was measured using a Taylor Hobson Talysurf contact profilometer with cut off length of 2.5mm and evaluation length of 12.5mm in accordance with ISO standard 4287:1997. SEM analysis of the cutting tool edges was conducted. A three-way analysis of variance (ANOVA) method was used to investigate the factorial variables on surface finish and delamination length.

Table 2. Factorial experiment variables

| Machining Environment | Cutting Tool | Machined Length (m) |
|-----------------------|--------------|---------------------|
| Cryogenic | MT | 0 |
| | | 4.2 |
| | | 8.4 |
| Dry | UD | 12.6 |

Additional degrees of freedom were provided by applying the sparsity of effects principle and evidence for assumptions of normality, constant variance and absence of outliers was verified using residual plots following the removal of non-significant effects.

3. Results and Discussion

3.1. Delamination

The extent of delamination was observed under the surface using the flash thermography approach. The images of the various coupons machined at tool wear of 8.4m is shown in Fig. 2 at equal magnification. Although the flash thermography also highlights the loose stitches it appears that the delamination of the top surface is worse under the dry cutting conditions as shown and is most severe with the UD cutting tool.

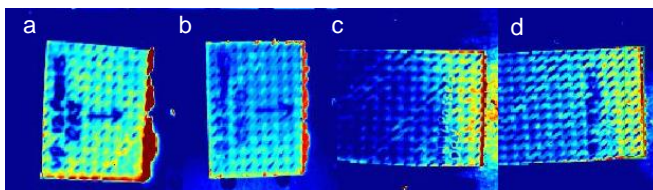


Figure 2. Flash thermography images of the set of coupons machined with tool wear incurred at 8.4m (a) UD and dry; (b) UD and cryogenic; (c) MT and dry; (d) MT and cryogenic.

The significant main and interaction effects found using the ANOVA method is shown in Fig. 3. It was revealed that the cutting tool design resulted in the largest main effect ($p=0.003$) on delamination in the top surface layer. It can be seen that the machined length is also significant ($p=0.012$) although the majority of this effect takes place within 0–4.2m indicating an initial accelerated tool wear period after which degradation in delamination due to tool wear becomes less significant. The interaction between cutting tool geometry and cutting environment was also significant ($p=0.028$), with each tool responding differently to the cutting environment. With the experimental data available it was not possible to show that any of the factors investigated were statistically significant in the bottom layer.

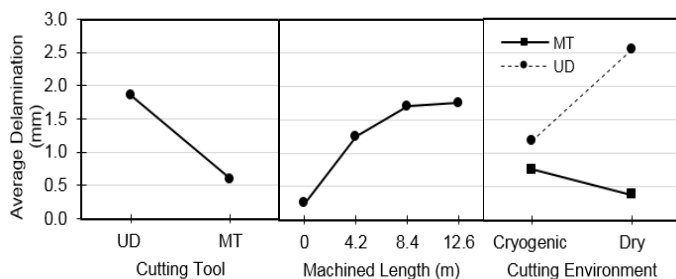


Figure 3. Delamination main effects cutting tool design and machined length; interaction effects of cutting environment and cutting tool design

This is possibly due to the reduced average delamination in this layer due to the more favorably orientated fibre direction. Higher statistical strength obtained through experimental replicates may be required to identify any specific trends.

3.2. Surface Roughness

The contact surface roughness measurements indicated that the cryogenic machining environment resulted in 28.1% average improvement in average surface roughness for both cutting tools. The surface roughness measurements and deviation with machined length is shown in Fig. 4.

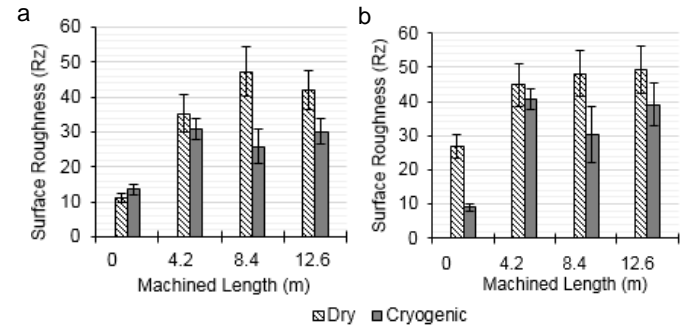


Figure 4. Surface roughness (R_z) measurements with standard deviation for machined lengths 0–4.2–8.4–12.6m for (a) MT cutting tool; (b) UD cutting tool

As with delamination, it can be seen that the surface roughness worsens with increased tool wear, with most degradation taking place within the first 4.2m. To ascertain the statistically significant effects once the tool is in its worn state, a separate 3-way 2 level ANOVA was conducted omitting the unworn cutting tool data. It was found that the cutting environment produced a main effect significant to 0.05 significance level, ($p=0.004$). This shows that the main effect of the cutting environment is the only factor able to improve surface roughness when machining with a worn tool. The large deviations in Fig. 4 may be attributed to the contact profilometer spanning multiple layers. As layers vary between favourable and non-favourable orientations for machining, this accounts for the wide distribution of measured values. Due to multiple measurements (>12) across the coupon machined edge a stable average value developed. However, a non-contact surface roughness measurement may be better suited for measuring these types of materials and quantifying a larger area of the surface [16].

3.3. Cutting Tool Wear

The degradation in delamination with the MT cutting tool in the cryogenic CNC machining environment may be attributed to the occurrence of a chipping mode tool failure. As shown in Fig. 5 (a) significant chip loss is present which may decrease the efficacy of the cutting tool to effectively remove material, whilst in the dry condition the cutting edge remains intact with small amounts of abrasive wear. Chipping mode tool failure was also apparent in the UD cutting tool in the cryogenic CNC machining environment as shown in Fig. 6(a) positioned above the abrasive wear zone. In contrast, the UD cutting tool in the dry CNC machining environment displayed only abrasive tool wear as shown in Fig. 6(b).

As the abrasive tool wear was similar for both cutting environments, the improved delamination performance of the UD cutting in the cryogenic cutting condition is most likely caused by stiffening of the matrix and the subsequent improvement of cutting mechanism. Further, study of tool wear

in cryogenic CNC machining is required to establish this trend with increased machined lengths. In addition as delamination was significantly worse than expected in the case of the UD cutting tool, it would be of benefit to optimise the investigate the combination of cutting parameter and/or cutting tool geometry to identify if improvements can be made. If possible, the cryogenic machining strategy could be of great benefit to high performance edge trimming of CFRP.

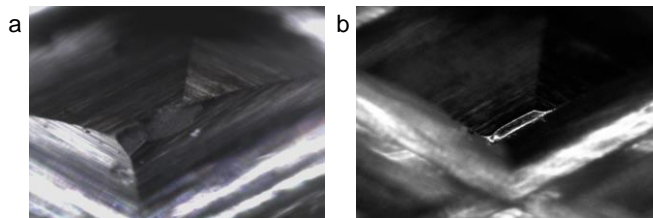


Figure 5. Optical Microscopy images of MT cutting tool (a) chipping mode tool failure found with cryogenic machining; (b) abrasive tool wear in the dry machining condition.

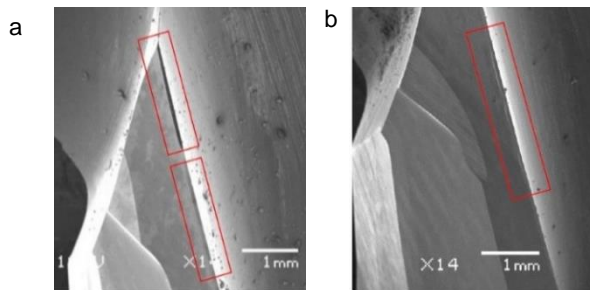


Figure 6. SEM images at X14 magnification (a) Chipping and abrasive tool wear in cryogenic condition; (b) Abrasive wear in dry machining condition

4. Conclusions

This research has highlighted the high degree of interaction of cutting tool geometry and machining environment in machining of CFRP. Based on the findings the following conclusions can be drawn:

- Cryogenic CNC machining improves the average surface roughness by 28.1% independent of cutting tool geometry compared to dry machining which is a significant improvement.
- Improvements to delamination length can be obtained through cryogenic CNC machining with the UD cutting tool indicating that this is a good strategy for improving quality of edge trimming CFRP, although geometrical optimisation of the cutting tool may be required.
- The MT cutting tool was highly susceptible to chipping under the cryogenic CNC machining, to preserve cutting edge integrity less extreme coolant methods may be of benefit with this cutting tool.

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